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Turbulent mixing in the seasonally-stratified western Irish Sea: a Thorpe Scale perspective

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Abstract

The seasonal thermocline in shelf-seas represents an important biogeophysical barrier to the vertical flux of nutrients into the photic zone. Episodic weakening of this barrier plays an important role in sustaining the sub-surface chlorophyll maximum in summer and hence impacts the carbon draw-down in the seasonally-stratified zones of the shelf seas. Here we present estimates of the rate of turbulent kinetic energy dissipation inferred from microstructure shear probes and compare them with dissipation rates inferred from a standard conductivity-temperature-depth instrument and from a fast thermistor (Thorpe Scale methodology) at a site in the seasonally-stratified Irish Sea. All methods show strong dissipation rates in response to tidal stresses near the bed (order $10^{-2}\,\mathrm{W\,m^{-3}}$) with qualitatively similar temporal and spatial patterns. In the interior of the water column, however, only the microstructure shear probe estimates resolve the mixing in the region of the thermocline.

1 Introduction

In stratified shelf seas, mixing is primarily driven by bottom-boundary tidal stresses, surface-boundary wind stresses and convective processes; although shear driven by near-inertial oscillations, internal tide and topographic lee waves may also be important sources of instability within the interior of the water column. These interior processes are particularly important if they drive a flux of nutrients across the base of the thermocline, into the sub-surface light layer, providing a link between the photic zone and the nutrient rich water below the thermocline. This turbulent flux of nutrients is crucial for sustaining the summer sub-surface chlorophyll maximum which has been estimated to fix up to twice as much carbon as the spring bloom (e.g., Richardson et al., 2000) and hence is a major component of the Shelf Sea Carbon Pump. Thus the ability to measure turbulent mixing in the region of the thermocline is essential in order to iden-

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tify the key physical processes which control the supply of nutrients to the sub-surface phytoplankton population (e.g., Rippeth, 2005).

Microstructure measurements of the rate of dissipation of turbulent kinetic energy (using shear probes) are now commonly used to study turbulent mixing in the ocean and shelf seas, however a technique that has seen a resurgence in recent years is the use of the Thorpe scale and the relationship between the Thorpe and Ozmidov scales to infer turbulent mixing (e.g., Stansfield et al., 2001; Finnigan et al., 2002). Use of the Thorpe Scale is appealing as it involves fewer assumptions than other "indirect" approaches based on shear and strain (which in any case are only applicable in the open ocean) and, because it uses standard oceanographic instrumentation as opposed to specialist microstructure dropsondes, thus it has the potential to provide wide ranging spatial and temporal estimates of the mixing levels.

The technique proposed by Thorpe (1977) involves the observation of density overturns. The Thorpe scale, or vertical overturning scale L_T, is defined as the root mean square (rms) of the vertical displacements, or Thorpe displacements L, required to re-order a measured profile of potential density so that it is gravitationally stable. If the Ozmidov scale (Ozmidov, 1965) is related to the Thorpe scale by $L_\mathrm{O} = 0.8L_\mathrm{T}$ as found by Dillon (1982) then the turbulent kinetic energy (TKE) dissipation rate, ε, can be calculated as $\varepsilon = (0.8L_\mathrm{T})^2N^3$. If the mixing efficiency is taken to be $\Gamma = 0.2$ diffusivity $K_v \simeq 0.1NL_\mathrm{T}^2$ can also be estimated, where N is the buoyancy frequency of the re-ordered density profile. Note that the coefficient of 0.1 is not firmly established (e.g., Caldwell and Moum, 1995). The expressions for K_v and ε, are valid only in regions that are stably stratified on the large scale and where mixing is a result of mechanical energy input, for example from winds or tides, rather than convective processes.

Thorpe scales have been used recently to provide valuable insight into small-scale mixing processes in a variety of different regions, however these studies are either from deep-ocean sites with rough topography (e.g., Finnigan et al., 2002), regions where large surface wind stresses, buoyancy fluxes and eddy processes are important (e.g., Thompson et al., 2007), regions of dense water overflow (e.g., Fer et al., 2004) or sites where there is a strong gravitational (estuarine) circulation (e.g., Stansfield et al., 2001; Galbraith and Kelley, 1996).

This is the first study of Thorpe scale estimates of small-scale mixing processes in a shelf-sea region where tidal stresses near the bed and surface buoyancy fluxes are the dominant inputs of mechanical energy. Moreover, few direct comparisons have been made between Thorpe scale and microstructure shear probe dissipation estimates, especially in the shelf seas.

In this paper we present results from an experiment specifically designed to investigate how independent estimates of TKE dissipation from microstructure shear probe measurements, from standard conductivity-temperature-depth (CTD) data and from fast thermistor data (Thorpe Scale methodology) compare. We also assess the ability of each technique to resolve the turbulent mixing in the region of the thermocline.

2 Study site and observations

Our study site was located in the western Irish Sea just landward of the seasonally-formed western Irish Sea front (henceforth referred to as the SWIS site). Here the tides are weak with peak currents of 0.3 to 0.5 $\mathrm{m\,s^{-1}}$. At the SWIS site the vertical water column structure has a distinct seasonal regime. The region stratifies during the heating season (April–October) when there is insufficient tidally-generated turbulent energy to maintain vertical mixing against input of surface buoyancy (Simpson and Hunter, 1974). This leads to the formation of the western Irish Sea front. An analysis of infra-red satellite sea-surface temperature imagery by Simpson and Bowers (1981) and early modelling work by Hill (1993) have shown that thermal stratification in summer at the SWIS site and the formation of the western Irish Sea front follows a remarkably consistent pattern from year to year.

On 16–17 July 2006 a 29 hour, single-point, time-series of water column structure, TKE dissipation rate and current velocity profile was made at a site in the summer-stratified western Irish Sea on board the R/V *Prince Madog* to study small-scale processes in the seasonal thermocline. The study site was centred on 53°43′ N, 5°30′ W and all measurements were made within a 2 km radius of this position. At this location in the Irish sea the water depth is 105 to 110 m. Figure 1 shows a sea-surface temperature image for the Irish Sea on 16 July 2006. The western Irish Sea front is clearly shown by the transition from warm to cool surface waters (temperatures above 14 °C to less than 13 °C) southwest of the Isle of Man; the approximate location of the SWIS study site is marked by the red cross. Thirty-minute average wind speeds during the time-series peaked briefly at 11.4 knots but were typically less than 8 knots giving calm sea-state conditions.

The sampling strategy was to make consecutive FLY dropsonde profiles for a period of about 30 min followed by two back-to-back CTD profiles, this pattern was repeated for the duration of the time-series (see Dewey et al., 1987, for a description of the FLY profiler). This yielded a data set of 172 microstructure profiles (FLY shear probe and fast thermistor data) and 58 fine-structure profiles (CTD data).

Simultaneous profiles of water column velocity structure were measured using a 300 kHz downward-looking acoustic doppler current profiler (ADCP) mounted to the bottom of the research vessel. This gave velocity information from 10 m below the sea-surface to within 14 m of the bottom in 4 m vertical bins and at 5 min intervals.

Turbulent kinetic energy dissipation rates were derived from the FLY shear probe data using the method described in Rippeth et al. (2003). High-frequency temperature was derived from the low frequency (20 Hz) temperature data and the high frequency (140 Hz) time derivative of temperature from the fast thermistor using the method of Mudge and Lueck (1994).

Since the temperature signal and its derivative are sampled separately at different temporal resolutions the method uses the following steps. First the low resolution temperature is interpolated to the high frequency resolution. Next the new high resolution temperature data are combined with the high-frequency $\mathrm{d}T\mathrm{d}t$ data. The combined data set is then filtered using a cut-off frequency, Ω_c, based on a differentiator gain of 1.85 which is known to be the gain of the $\mathrm{d}T\mathrm{d}t$ circuit (see Mudge and Lueck, 1994). Finally

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the filtered high-frequency signal is converted to physical units by polynomial regression to the low frequency temperature.

Thorpe scales and hence TKE dissipation rates were calculated using 0.1 m vertical averages of both the CTD temperature data and the high-frequency temperature data from the FLY profiler using the methods described in e.g. Stansfield et al. (2001) and Galbraith and Kelley (1996). As the surface to bottom range in salinity during the time-series is less than 0.2 while the temperature range is greater than 6 °C, and because spice gradients are all greater than zero (indicating that density gradients are due to temperature changes) we conclude that temperature profiles are sufficient for identifying overturning regions. Note also that in determining the dissipation of a single overturn we have taken the mean value of buoyancy frequency over the reordered region of the overturn since overturns occur mostly in regions of low stratification (Alford and Pinkel, 2000).

Following Johnson and Garrett (2004) we have calculated the non-dimensional parameters Q and n which describe the two limiting factors of overturn detection: density (in our case temperature) resolution and vertical (pressure) resolution. Using values from our study, and sensor resolutions given in Stansfield et al. (2001, Table 1), the amplitude of the noise scaled by the temperature change over the section is

$$Q = \frac{\delta T}{(\partial T/\partial z)H} \leq 0.001 \tag{1}$$

and n is given by

$$n = \frac{H}{h} \approx 1000 \tag{2}$$

where δT is the instrument noise, $\partial T/\partial z$ is the stratification, H is the vertical extent of the water column sampled, and h is the vertical sampling interval. For $nQ > 1$, temperature resolution limits overturn detection, while for $nQ < 1$, vertical resolution limits overturn detection (Stansfield et al., 2001). Here $nQ < 1$. Hence in $\log(n)$ vs. $\log(Q)$

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space our data lies in the upper left hand corner of the non-dimensional parameter space where overturn detection and resolution is improved (see Johnson and Garrett, 2004; Thompson et al., 2007)

3 Stratification, shear and turbulence structure

Figure 2 shows the time series of stratification from the CTD, shear from the ADCP, TKE dissipation rate from the FLY shear probes, the CTD temperature Thorpe scales and the FLY high resolution temperature Thorpe scales; data from the top 10 m of the water column are not shown. The mean vertical profile of each parameter is shown to the right of the time-series plot.

The water column is stratified (Fig. 2a) with a buoyancy frequency, N, of 0.007 s^{-1} in the bottom boundary layer, increasing to a maximum of 0.021 s^{-1} in the thermocline between 20 and 30 m, decreasing to a local minimum of 0.015 s^{-1} between 10 and 20 m and increasing back to 0.019 s^{-1} at 5 m. Shear (Fig. 2b) peaks across the thermocline and in the bottom boundary layer, with values exceeding 0.017 s^{-1}. The TKE dissipation rates from the microstructure shear probe (Fig. 2c) and Thorpe scale methods (Fig. 2d and e) show qualitatively similar temporal and spatial patterns.

There is a strong signal in response to tidal stresses near the bed (peak values are of order 10^{-2} $W m^{-3}$) which agrees quantitatively with values found at a nearby site in the Irish Sea by Simpson et al. (1996). As the semi-diurnal barotropic tidal current weakens between peak ebb and peak flood the velocity shear induced by the interaction of the tidal flow with the seabed propagates into the interior of the water column (up to about 40 m above the sea-bed) and results in a clear quarter-diurnal signal of enhanced levels of TKE dissipation (Simpson et al., 2000). The quarter-diurnal signal is most evident in the FLY shear probe TKE dissipation rate data but is also discernable in the CTD-derived and to a lesser extent in the fast-thermistor-derived estimates. That the CTD-derived TKE dissipation estimates show the quarter-diurnal periodicity more

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clearly than the fast-thermistor derived estimates is somewhat surprising as the CTD data has only one-third the temporal sampling resolution of the FLY data sets.

Mean TKE dissipation rates in the bottom boundary layer (lower 40–50 m) are $4\times10^{-4}\,\mathrm{W\,m^{-3}}$ for both the shear-probe and fast-thermistor derived estimates, but a little higher at $6\times10^{-4}\,\mathrm{W\,m^{-3}}$ for the CTD estimates. In the thermocline however both Thorpe scale derived TKE dissipation estimates are one to two orders of magnitude lower, at less than $10^{-6}\,\mathrm{W\,m^{-3}}$, whereas the shear probe derived estimates are of order $10^{-5}\,\mathrm{W\,m^{-3}}$. Based on the stratification and the TKE dissipation rates from the FLY profiler shear probe data, the Ozmidov scale, which sets the vertical length scale of the mixing, is expected to be much less than 1 m in the region of the thermocline and of order 15 m in the bottom boundary layer. Thus the Thorpe-scale methodology underestimates the mixing in the thermocline where the stratification reduces the overturning scale, but can resolve the turbulent mixing in the bottom boundary layer. The time-mean profile of TKE dissipation rate from the microstructure shear probe data show that although the thermocline is highly restrictive on the mixing length scale (all methods show this) there is a distinct thermocline maxima suggesting an external source of energy.

Figure 3 shows TKE dissipation rates binned into a parameter space defined by 4 m stratification and 4 m shear variance (only bins containing 3 or more dissipation estimates have been plotted). For the shear probe and both Thorpe scale TKE estimates, dissipation rate increases with decreasing stratification and increasing shear, however dissipation rates are moderately elevated at low stratification values for all values of shear measured. This pattern may be because the mechanical energy input into the mixing is variable in time and is at a maximum on peak ebb or flood tidal currents. In addition, as the peak dissipation propagates vertically into the interior of the water column, high dissipation rates can be associated with regions of comparatively low shear and stratification (see Fig. 2b and c). Note that the Thorpe scale methodology gives no dissipation rate estimate if no overturn is detected. The difference between the fast thermistor and CTD-derived dissipation rates is most likely because the bottom

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boundary layer is relatively well mixed with low stratification and high shear and that the temperature differences in this region are not resolved by the FLY fast thermistor.

In a recent study of mixing on the New England Shelf in late-summer, MacKinnon and Gregg (2003) compare the pattern of observed TKE dissipation rates, binned by 4 m stratification and 4 m shear variance, with the patterns predicted by the Gregg–Henyey dissipation rate parameterization (Gregg, 1989) and a new parameterization suggested by the authors (see MacKinnon and Gregg, 2003, Fig. 13). For the Gregg–Henyey parameterization (based on open ocean, mid-latitude, observations) TKE dissipation rate increases with increasing shear for all stratification values, unsurprisingly this pattern did not match the observations from the shelf where much of the shear was due to the low frequency, large-scale, internal motions (including inertial oscillations and evidence of an internal tide). The new parameterization proposed by MacKinnon and Gregg (2003) showed closer agreement with their observations from the shelf whereby TKE dissipation rates increased with increasing shear and increasing stratification. Neither parameterization matches our observations. This suggests that the pattern of TKE dissipation rate in shear/stratifcation space may be an indicator of the dominant physical processes driving the mixing, in our case tidal stress in the bottom boundary layer and surface buoyancy and wind stresses (not resolved by the CTD or fast thermistor observations).

4 Conclusions

Our results indicate that where tidal stresses are the dominant input of mechanical energy into the turbulence the TKE dissipation rate increases with decreasing stratification over the entire range of shear values measured. This pattern is markedly different to that observed by MacKinnon and Gregg (2003) over the New England Shelf where internal shear was driven primarily by large scale, low-frequency, internal motions. We suggest that interpreting TKE dissipation rates in a shear/stratifaction parameter space may give important clues as to the underlying physical processes driving the turbu-

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lence. However, caution must be exercised as 4 m shear and 4 m stratification are unlikely to be the relevant parameters in a region where turbulent mixing scales are on the order of cm. Thus the transition to turbulence, for whatever process is driving thermocline mixing, is likely not only under resolved but completely ignored.

We have shown that the Thorpe scale methodology applied to temperature data from a standard CTD may be used to calculate TKE dissipation rates in the bottom boundary layer of a tidally dominated, thermally stratified, shelf-sea. However, this approach does not resolve the small-scale mixing occurring in the region of the thermocline even when the high-frequency temperature data is used. This precludes use of the Thorpe scale technique for studying carbon and nutrient fluxes in the region of the thermocline and sub-surface chlorophyll maximum, thus observational studies of these processes must appeal to microstructure shear probe measurements.

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References

Alford, M. and Pinkel, R.: Observations of overturning in the thermocline: the context of ocean mixing, J. Phys. Oceanogr., 30, 805–832, 2000. 2146

Caldwell, D. R. and Moum, J. N.: Turbulence and mixing in the ocean, Rev. Geophys., 81, 1385–1394, 1995. 2143

Dewey, R. K., Crawford, W. R., Gargett, A. E., and Oakey, N. S.: A microstructure instrument for profiling oceanic turbulence in coastal bottom boundary layers, J. Atmos. Ocean. Tech., 4, 288–297, 1987. 2145

Dillon, T. M.: Vertical overturns: a comparison of Thorpe and Ozmidov scales, J. Geophys. Res., 87, 9601–9613, 1982. 2143

Fer, I., Skogseth, R., and Haugan, P.: Mixing of the Storfjorden overflow (Svalbard Archipelago) inferred from density overturns, J. Geophys. Res., 109, C01005, doi:10.1029/2003JC001968, 2004. 2143

Finnigan, T. D., Luther, D. S., and Lukas, R.: Observations of enhanced diapycnal mixing near the Hawaiian Ridge, J. Phys. Oceanogr., 32, 2988–3002, 2002. 2143

Galbraith, P. S. and Kelley, D. E.: Identifying overturns in CTD profiles, J. Atmos. Ocean. Tech., 13, 688–702, 1996. 2144, 2146

Gregg, M. C.: Scaling turbulent dissipation in the thermocline, J. Geophys. Res., 94, 9686–9698, 1989. 2149

Hill, A. E.: Seasonal gyres in shelf seas, Ann. Geophys., 11, 1130–1147, 1993, http://www.ann-geophys.net/11/1130/1993/. 2144

Johnson, H. L. and Garrett, C.: Effects of noise on Thorpe scales and run lengths, J. Phys. Oceanogr., 34, 2359–2372, 2004. 2146, 2147

MacKinnon, J. A. and Gregg, M. C.: Mixing on the late-summer New England shelf-solibores, shear, and stratification, J. Phys. Oceanogr., 33, 1476–1492, 2003. 2149

Mudge, T. D. and Lueck, R. G.: Digital signal processing to enhance oceanographic observations, J. Atmos. Ocean. Tech., 11, 825–836, 1994. 2145

Ozmidov, R. V.: On the turbulent exchange in a stably stratified ocean, Izv. Acad. Sci. USSR, Atmos. Oceanic Phys., 1, 493–497, (English translation), 1965. 2143

Richardson, K., Visser, A. W., and Pedersen, F. B.: Subsurface phytoplankton blooms fuel pelagic production in the North Sea, J. Plankton Res., 22, 1663–1671, 2000. 2142

Rippeth, T. P.: Mixing in seasonally stratified shelf seas: a shifting paradigm, Phil. Trans. Roy. Soc. A, 363, 2837–2854, 2005. 2143

Rippeth, T. P., Simpson, J. H., Williams, E., and Inall, M. E.: Measurement of the rates of production and dissipation of turbulent kinetic energy in an energetic tidal flow: red wharf bay revisited, J. Phys. Oceanogr., 33, 1889–1901, 2003. 2145

Simpson, J. H. and Bowers, D.: Models of stratification and frontal movement in shelf seas, Deep-Sea Res., 28, 727–738, 1981. 2144

Simpson, J. H. and Hunter, J. R.: Fronts in the irish sea, Nature, 250, 404–406, 1974. 2144

Simpson, J. H., Crawford, W. R., Rippeth, T. P., Campbell, A. R., and Cheok, J. V. S.: The vertical structure of turbulent dissipation in shelf seas, J. Phys. Oceanogr., 26, 1579–1590, 1996. 2147

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Simpson, J. H., Rippeth, T. P., and Campbell, A. R.: The phase lag of turbulent dissipation in tidal flow, in: Interactions between Estuaries, Coastal Seas and Shelf Seas, edited by: Yanagi, T., Terra Scientific, Tokyo, 57–67, 2000. 2147

Stansfield, K. L., Garrett, C. J. R., and Dewey, R. K.: The probability distribution of the thorpe displacement within overturns in juan de fuca strait, J. Phys. Oceanogr., 12, 3421–3434, 2001. 2143, 2144, 2146

Thompson, A. F., Gille, S., MacKinnon, J., and Sprintall, J.: Spatial and temporal patterns of small-scale mixing in Drake Passage, J. Phys. Oceanogr., 37, 572–592, 2007. 2143, 2147

Thorpe, S. A.: Turbulence and mixing in a Scottish Loch, Phil. Trans. Roy. Soc. A., 286, 125–181, 1977. 2143

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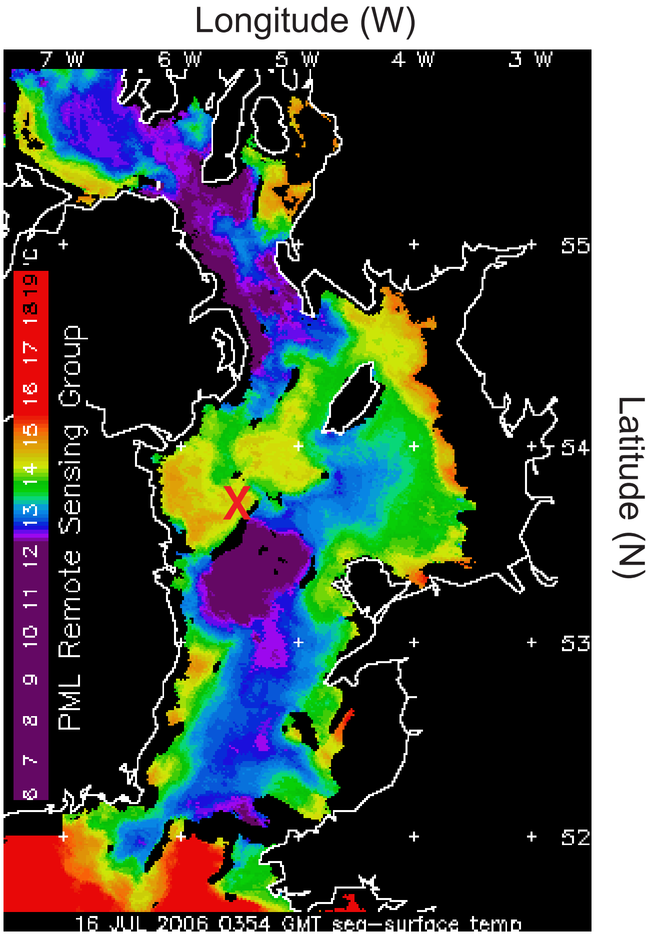

Fig. 1. Satellite image of sea-surface temperature in the Irish Sea on 16 July 2006. The colour scale ranges from 6 to 19 °C with temperatures less than 12 °C shown in blue/purple and temperatures warmer than 15 °C shown in orange/red. The large red cross denotes the approximate location of the SWIS study site at 53°43′ N, 5°30′ W.

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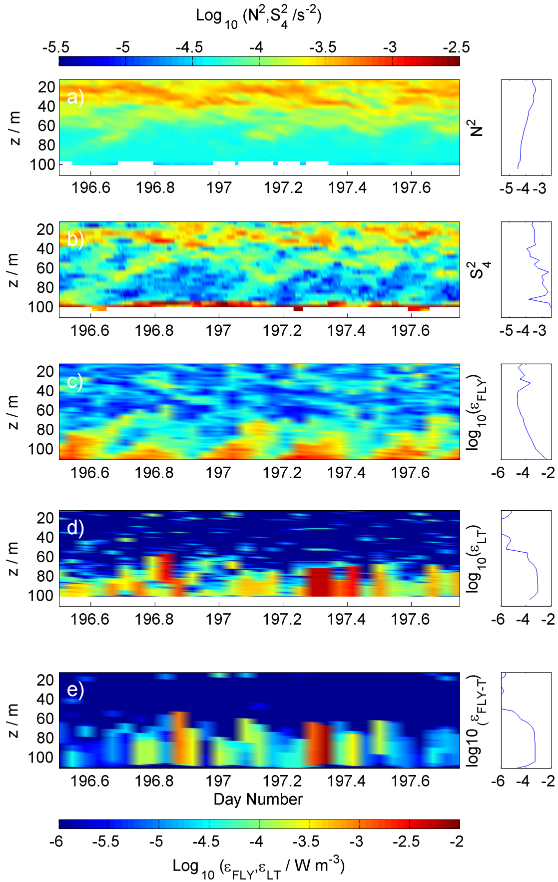

Fig. 2. Time series of buoyancy frequency **(a)**, shear variance (4 m) from the shipboard ADCP **(b)**, TKE dissipation rate from the FLY primary shear probe **(c)**, TKE dissipation rate from Thorpe scale estimates using the CTD data **(d)**, and TKE dissipation rate from Thorpe scale estimates using the FLY fast thermistor data **(e)**. TKE dissipation rates in panels **(c)**, **(d)** and **(e)** are hourly averages to account for differences in the sampling interval. Time-mean profiles of each parameter are shown to the right of each panel. The y-axis range is from 10 m to 110 m.

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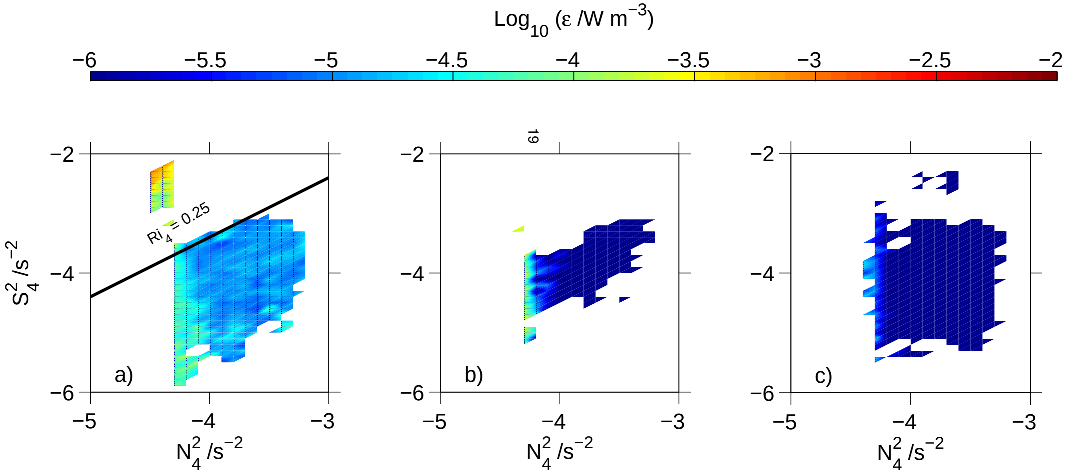

Fig. 3. **(a)** TKE dissipation rate from the FLY shear probes binned into a parameter space defined by 4 m stratification and 4 m shear variance, **(b)**, **(c)**. As **(a)** but for the Thorpe scale derived CTD and fast thermistor TKE dissipation rate estimates, respectively.